MFR PAPER 1220

Impact of Cooling Waters on the Aquatic Resources of the Pacific Northwest

DONOVAN R. CRADDOCK

Craddock

Donovan R. Craddock is with the Northwest Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. East, Seattle, WA 98112.

INTRODUCTION

Aquatic animals, with the exception of aquatic birds and mammals, are cold-blooded or poikilothermous, which means that their internal body temperature approximates that of the environment in which the animal lives. Since the aquatic environment has a comparatively narrow range of temperature, fish and shellfish do not have wide temperature tolerances. They can never adjust their body temperature below or above that of the surrounding water; therefore, they suffer damage or death from temperatures higher or lower than their normal temperature range. In addition, the life processes, growth, and activity of cold-blooded animals are governed by the temperature of their environment.

The following discussions are related solely to the effect that man's industrial activities, especially electrical power generation, have or may have on the temperature of the aquatic environment of the Pacific Northwest area and the subsequent effect of these alterations on the aquatic biota.

The demand for electrical power in the United States generally, and in the Pacific Northwest specifically, is increasing at an alarming rate. The Bonneville Power Administration (BPA) of the U.S. Department of the Interior estimates that the firm energy sources in the Pacific Northwest will almost triple in the next 20 years. Since most of the economically feasible hydroelectric sites have already been developed, the bulk of the new power will be from thermal generation, both nuclear and fossil fuel, such as coal and oil.

Thermal nuclear power generation is very inefficient. Approximately two-thirds of the total heat generated is wasted and must be dissipated into the environment. This has caused concern for the aquatic environment and its biota since the waste heat from thermal electric plants is normally disposed of in rivers, lakes, estuaries, and the sea. A 1,000-megawatt thermal nuclear plant, with once-through cooling will discharge as much as 2,000 cubic feet per second of water heated an average of 19.4°F (10.8°C) above the ambient temperature in fresh water and 25°F (14°C) in salt water (Coutant, 1970). Little is known of the effects that the addition of such tremendous amounts of heat would have on marine resources. The major indigenous fishery resources of the Pacific Northwest are both cold-water and anadromous species. This creates special concern for their welfare with the advent of widespread thermal pollution in the aquatic environment. This report describes the present and predicted future sources and volumes of cooling waters returned to the marine environment in the region; it reviews the physical and biological effects that such cooling water may have on the marine resources.

SOURCES OF COOLING WATER

Present Sources

The Pacific Northwest has obtained almost all of its electric energy from hydrogeneration up to the present time. There are 161 hydroelectric projects in the region (Bonneville Power Administration, 1972). Because of a limited supply of alternate energy sources and a generous supply of hydropower, the Pacific Northwest has used electric energy at an even greater rate than the rest of the nation. However, most of the feasible hydropower sites have been developed, and the region's electrical suppliers are turning to steam electric generators, mostly nuclear fueled.

Each of the different methods of generating electricity has harmful as well as beneficial effects on the environment. Hydroelectric development, in the past, has blocked or otherwise hindered anadromous fish runs, in addition to inundating spawning areas. However, it has benefited the fisheries by controlling floods and releasing additional water during the low-flow periods in the late summer and fall. Steam-electric plants—particularly those that are nuclear-fired—return great quantities of heated water to the environment. Laboratory and on-site experiments have shown this to be detrimental to the aquatic life in the immediate area of the discharge. On the other hand, experiments have shown certain instances where heated water at safe levels has induced greater productivity and growth rates of aquatic animals (Bell, 1971).

There are numerous sources of thermal pollution in the waters of the Pacific Northwest, mainly around large metropolitan and industrial areas. These probably vary from purely heated water to a multitude of combinations of heated water with other pollutants. A survey of the lower Columbia River revealed 19 thermal pollution outfalls between Bonneville Dam and the mouth of the river. It was calculated that these outfalls put sufficient heat into the river during the summer to raise the temperature of the entire flow by 0.5°F (0.3°C). The shore water where the outfalls are usually located could be expected to increase more than 0.5°F.

The largest single source of man-made heat injected into the Columbia River comes from the Washington Public Power Supply System plant at Hanford, Wash. It was the largest thermal nuclear plant in the United States when it went into production in 1966 and it was the first in the Pacific Northwest. The electrical power produced at this plant requires the diversion of 1,240 cubic feet per second of cooling water from the Columbia River. This quantity of water diverted daily from the Columbia River was more water than used daily for domestic purposes in the entire state of Texas and twice the daily domestic consumption of the entire city of Los Angeles (Snyder, 1969). This volume of water is increased by 30°F (17 °C) over normal river temperatures as it is pumped through the condenser of the plant. The effluent cooling water from the Hanford plant is discharged into the mainflow of the Columbia River.

The only other large thermal electric plant operating in the region is the huge new fossil fuel plant at Centralia, Wash. It apparently does not contribute substantially to thermal pollution of the aquatic environment because it has cooling towers, and most of the heat is discharged via the towers into the atmosphere.

Most of the thermal power generation in tidewater on the west coast is in California where in 1968 there were 2 nuclear and 21 conventional plants; Oregon had 7 conventional plants and Washington only 3 (North and Adams, 1969).

Future Sources

As mentioned earlier, most of the economic hydropower resources will soon be developed and some authorities believe that by the early 1990's hydropower resources will be used to serve peak demands and thermal plants will operate as baseload plants. Figure 1 (Bonneville Power Administration, 1972) depicts the future dependence on thermal electric power in the Pacific Northwest. A hydrothermal program developed by BPA to meet the predicted demand for electricity calls for the construction of 20 thermal plants in this region by 1990 (Bonneville Power Administration, 1969). If these plants used once-through cooling, it would mean that approximately 32,000 cubic feet per second of cooling water would be returned to the environment at 18°F (10°C) above ambient. A volume of 32,000 cubic feet per second is approaching one-half of the low flow of the Columbia River. This volume of heated water could obviously have far-reaching effects on the environment.

The search for sites to locate the thermal nuclear plants has concentrated on the Columbia River, the

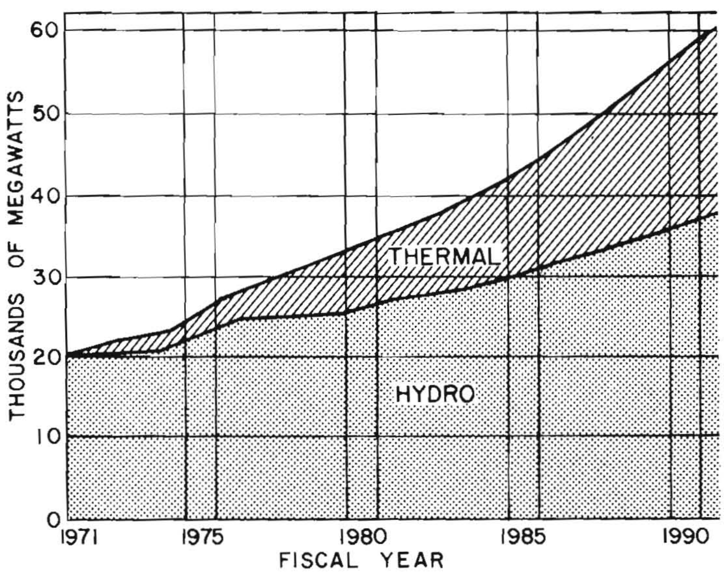

Figure 1.—Predicted future dependence on thermal electric power in the Pacific Northwest (Bonneville Power Administration, 1972).

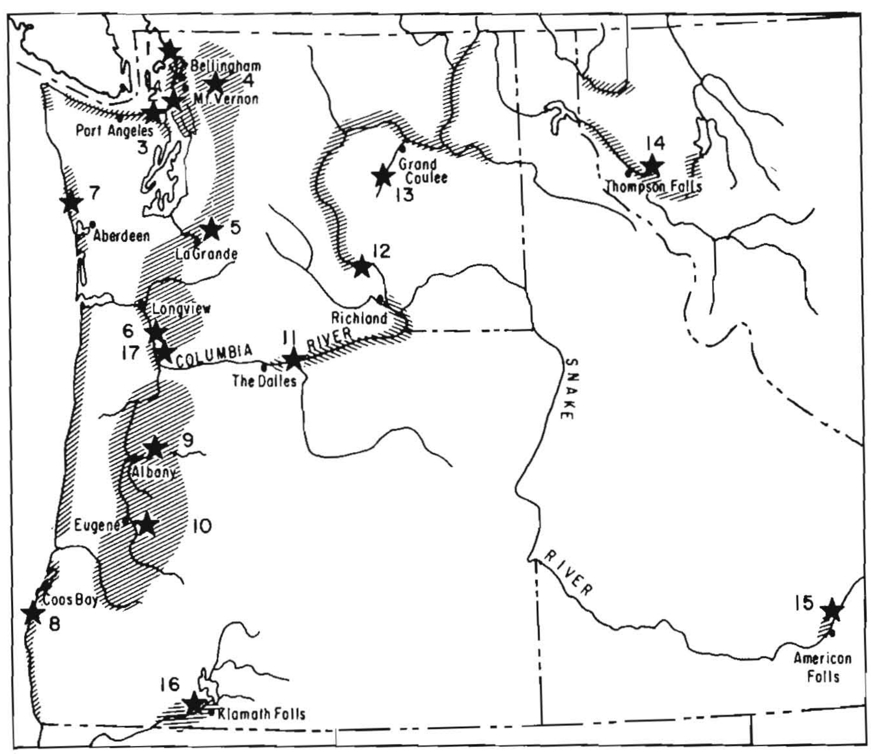

Figure 2.—Proposed location of thermal electric power plants in the Pacific Northwest. (From Snyder, 1968.)

coasts of Oregon and Washington, the Strait of Juan de Fuca, and Puget Sound (Fig. 2). However, possible sites for nuclear power plants have included northwestern Montana and southeastern Idaho (Battelle Northwest, 1967). It would be economically advantageous to locate the plants close to the major centers of industry and population, but many factors, especially the availability of cooling water, will govern the location of plants.

The Trojan Nuclear Plant at Prescott, Oreg., is scheduled to go into operation in 1976. Studies at the site by the National Marine Fisheries Service established that once-through cooling would be detrimental to anadromous fish runs of the Columbia River. To alleviate the problem, the builders (Portland General Electric, Eugene Water and Electric Board, and Pacific Power and Light) included a closed cycle, natural draft cooling tower which will essentially eliminate returning large quantities of hot water to the river. Figure 3 shows this very expensive structure. A similar plant is contemplated across the river at Kalama, Wash.; other nuclear plants are scheduled for construction on the Skagit and Chehalis rivers in Washington.

Floating offshore thermal nuclear power plants are a real future possibility (Russell, 1974). Two plants proposed for 3 miles off the coast of New Jersey will generate 1,150 megawatts each and pump 2 million gallons of cooling water per minute, heated 17°F (9°C), back into the sea. Offshore floating-nuclear-power plants (OFNPP) may be an answer to the lack of suitable onshore generating sites where adequate cooling water is available. Of course, a major question regarding the proposed OFNPP's concerns the effect they would have on the marine environment and resources.

PHYSICAL EFFECTS OF COOLING WATERS ON THE AQUATIC ENVIRONMENT

Temperature affects many physical properties of water including density, viscosity, vapor pressure, and solubility of dissolved gases. Both density and viscosity decrease with increased temperature which accelerates settling velocities and has an effect on the deposition of sediment and sludge in rivers, reservoirs, and estuaries.

Slight differences in density may cause stratification in bodies of water, inhibiting vertical mixing and oxygen transfer to lower waters. Sufficient oxygen is one of the basic requirements for most living organisms. The solubility of oxygen decreases with increasing temperature and may result in oxygen levels less than optimum for a healthy aquatic environment. Atmospheric nitrogen, which is not normally important to good water quality, may reach supersaturation through rapid warming or pressure reduction, as occurs in condenser systems, causing serious problems to fish. Increased temperature also increases the rate of chemical or biochemical reactions and, in the presence of biodegradable organic material, the biochemical oxygen demand may be so great as to deplete the oxygen supply.

Fast flowing streams or rivers have advantages over lakes or reservoirs in disposing of cooling waters. They rapidly transport heated water away from outfalls, minimizing temperature buildup at the discharge point. The turbulence eliminates stratification and makes the exchange of heat between the surface and the atmosphere more rapid. Surface exchange coefficients (U_c) for lakes are about 100 Btu (British thermal units)/ft^2 · day · °F (temperature difference between air and water). Impounded reaches reaches of the Columbia River have U_c values of 130 to 160, whereas values for swift-flowing reaches are from 200 to 300 (Battelle Northwest, 1967). Heat added to a river may be dissipated twice as fast from a swift-flowing section as from an impounded section. Calculations indicate that 85 percent of a 1°C (1.8°F) increase would persist 204 miles downriver in the summer but

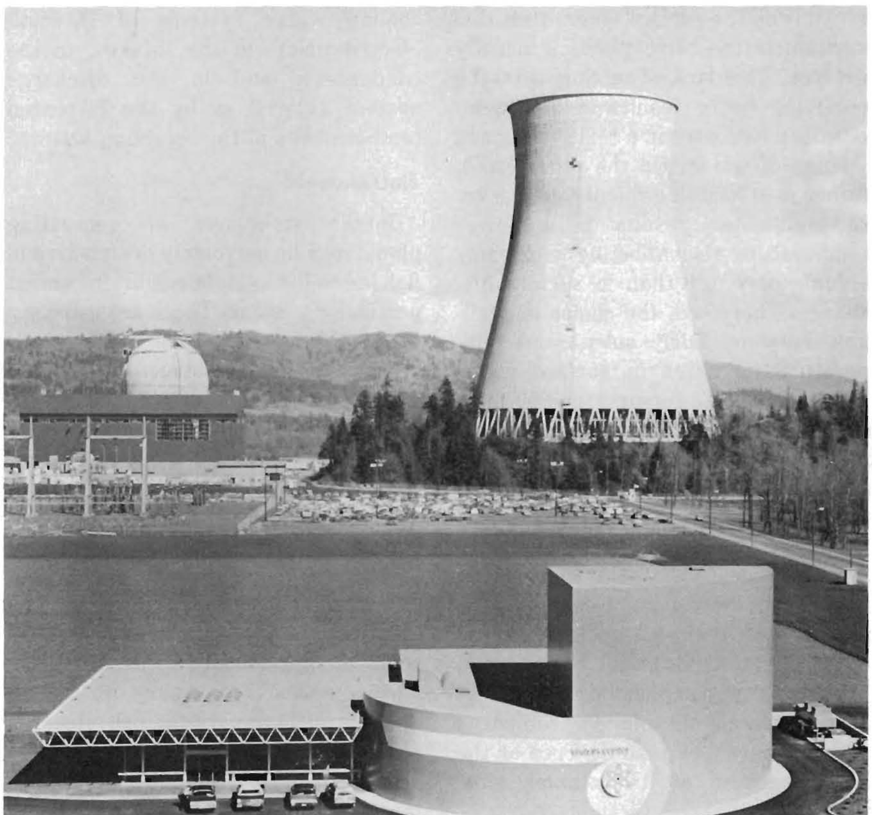

Figure 3.—The Trojan thermal nuclear electric power plant and natural draft cooling tower on the Columbia River (Portland General Electric Company, 1975).

only 65 percent would persist in the winter. It is difficult to generalize how long heat will persist because surface area, time, and current velocity all enter into the exchange process and each should be considered.

In a deep lake or impoundment, the water is usually stratified. In the summer the cool stagnant water of the bottom is separated from the warmer water of the surface by the transition zone. Heated water added to the surface will spread out in relatively thin layers (3 to 6 feet deep) over a larger and larger area until its density approximates that of the surface water. Very little of the effluent will reach the bottom until the fall of the year, at which time, the lake's stratification is broken and the waters mix.

The dissipation of heat from nuclear power plants is estimated to require about 2,000 acres of lake or impoundment surface for each 1,000 megawatts. Cooling water discharge to the surface of the receiving water generally remains on the surface where heat dissipation to the atmosphere is usually greater. This lack of mixing with the receiving water results in high temperature increases in a relatively small volume of water. On the other hand, diffusion of heated effluent into the receiving water results in a lower temperature rise affecting a greater volume of water than in surface discharge. Therefore, the choice is available between fairly substantial temperature increases in surface water versus moderate temperature increases in a much greater volume of the receiving water. The preceding would also be true of a saltwater installation with the exception that the pattern of heated waters would be much more complex because of the periods of flood, ebb, and slack tides and the intrusion of fresh water. An enclosed body of water like Puget Sound could have a very complicated pattern of heated water dissipation compared with the Strait of Juan de Fuca or the ocean because of its complex tidal patterns.

Heat dissipation in estuaries is complicated by the natural stratification caused by the intruding wedge of salt water on the bottom and the fresh or brackish water on top which would be reinforced by the addition of heated water. Although the general movement of the water would be seaward with the flow of the river, there would be the added complexities of the tidal cycle.

Dissipation of heated water at a marine site depends on many things, including ambient water temperature, air temperature, tidal currents, freshwater influx, and plant intake and discharge arrangements. In general a 2,000-megawatt plant (many are planned) will affect the immediate area of a plant to a radius of 6,000 yards. Beyond this point the temperature difference would be too low to maintain stratification (less than 3°F (2°C). Each plant and site is a special case and generalizations are of questionable value, but fairly accurate predictions of the thermal regime expected at a particular site may be made (Adams, 1969).

BIOLOGICAL EFFECTS OF COOLING WATER

Marine organisms are affected by cooling water systems of thermal-electric plants at the intakes, in the condensers, and in the discharge system as well as by the increased temperatures of the receiving waters.

Entrainment

Intake structures of generating plants may be extremely destructive of fish life under certain conditions and at particular seasons. There are usually a series of gates, trash racks, and screens at an intake structure, grading from coarse (to eliminate heavy debris) down to fine screen of 3/8- or 1/4-inch mesh to exclude finer particles that could block the 1-inch diameter condenser tubes. Fish may be impinged and injured or killed at any one of these, depending on the size of the fish and the velocity of the water at the structure. Impinged fish and debris are removed periodically by some mechanized means, but usually no special effort is made to save the fish. Records to assess the true loss of fish caused by impingement at generating plants are few but those that do exist demonstrate the magnitude of the problem. At a generating plant on the Hudson River in New York, almost 1 1/2 million fish were killed in a 2-month period during the winter of 1969-70 (Edsall and Yocom, 1972); the testing of two new pumps at this plant killed so many fish in one month that the operating company was fined over $1 1/2 million (Sport Fishing Institute, 1972a). Impingement takes it toll of aquatic organisms in either the freshwater or marine environment and could be a serious problem wherever thermal electric plants are built.

Myriads of important marine organisms are too small to be screened from the condenser cooling system. They include: fingerling fish, fish eggs and larvae, eggs and larvae of invertebrates, and the balance of the zooplankton that comprises important members of the marine food chain. These small organisms are carried through the condenser cooling system where they encounter many adverse conditions: collision with the internal surfaces, extreme temperature shock, pressure and temperature changes causing gas embolism, and toxic chemicals used as biocides. Several studies have been made of the survival of fish eggs and larvae in condenser systems, almost all of which indicate a high loss. At a thermal nuclear plant in Connecticut, up to 80 percent of the entrained larvae died in passage through the condenser cooling system and none survived passage through the condenser and discharge canal when discharge temperatures were 86°F (30°C) and above (Marcy, 1971). Similar results were experienced at plant after plant where studies have been made of survival of larval fish entrained in cooling systems (Marcy, 1973). Striped bass, menhaden, whitefish, herring, and smelt larvae have suffered heavy losses through entrainment. Losses similar to those mentioned above could be expected at plants in the Pacific Northwest having once-through cooling; many of the same or similar species are present, in addition to Pacific salmon, genus *Oncorhynchus*. Salmon fingerlings, especially pink, *O. gorbuscha*, and chum salmon, *O. keta*, would be vulnerable to power plant entrainment since they migrate in dense schools near shore where intakes may be located.

Distribution

One of the obvious biological effects of power plant discharges of waste heat in other parts of the country has been a local alteration in the seasonal distribution of fishes. It is a natural tendency for aquatic organisms to seek the temperature where growth and other life processes are at an optimum. Therefore, they may seek cool water in the summer and warm water in the winter. Elevated temperatures in discharge areas may collect numerous species of warm water fish in summer while repelling cold water species. In winter, when effluent temperatures may be tempered by lower river temperatures, all species may be attracted.

Most fish are able to adjust to or avoid temperature changes if they are gradual. However, the operation of power plants can cause both rapid increases and decreases of temperature in the vicinity of the discharges. Reversing the flow through condensers to remove fouling may cause sharp temperature increases, killing fish in the discharge area. Plant shutdowns in winter may expose the collected fish to equally lethal cold-water shock. These disasters have befallen manhaden, anchovies, bluefish, striped bass, and herring—species similar to those in this area. Fish kills as great as 25 tons per month have been estimated for the plants operating between San Diego and Ventura on the California coast. Although some of these problems may be moderated in Puget Sound and coastal locations in the Pacific Northwest because of a more stable year-round water temperature regime, serious loss of fish could result. It has been found that the fully marine and sublittoral species are less tolerant of high temperatures than estuarine or intertidal forms.

Temperature Tolerance

The chemical and biochemical processes of an animal's body accelerate with increasing temperature; normally the metabolic rate doubles with each 19°F (11°C) increase. As temperatures rise, an animal's respiration rate increases along with the heartbeat rate, which consequently increases the demand for oxygen. At higher temperatures the hemoglobin of the blood has reduced carrying capacity for oxygen. The combination of increased demand for oxygen and decreased efficiency for obtaining it causes a severe stress on the organism. This may eventually cause death or one or more of the many sublethal effects.

Several extensive bibliographies on the effects of increased temperatures on aquatic organisms have been prepared (Naylor, 1965; Kennedy and Mihursky, 1967; and de Sylva, 1969). Much of the work is concerned with freshwater rather than marine life, but one recent report has compiled a schematic representation for thermal requirements for different life processes of Pacific salmon (Fig. 4).

The upper and lower lethal temperatures depend on the temperature at which an organism has been acclimated. There are, of course, upper and lower limits above and below which an organism is unable to survive, regardless of acclimation (Brett, 1956). Temperature acclimation and thermal tolerance information is useful in many ways, but it does not provide information on the condition of the organism before it reaches the lethal temperature or of the irreversible physiological effects that may occur well below the lethal temperature.

Tolerance to temperature increases may depend on an organism's geographical range as well as its ecological habitat. For example, tropical animals may live at temperatures only a few degrees below their death point, while arctic species may normally live many degrees below their upper thermal death point. Adult Arctic fishes can usually be acclimated to temperatures far above their normal temperature, whereas tropical species ordinarily cannot be acclimated to temperatures much higher than their normal temperatures. Temperate species have generally exhibited a wide range of experimental lethal temperatures.

Gradual acclimation to higher temperatures increases an organism's ability to survive high temperatures but decreases its ability to survive low temperatures. This accounts for the great loss of fish collected by heated water in the winter that are subjected to sudden cold water by a plant shutdown. Most marine organisms seem to be able to adjust to increasing temperatures more rapidly than to decreasing ones.

The natural habitat of a particular species influences its range of temperature tolerance. Estuarine species are normally more tolerant of temperature fluctuations than sublittoral or littoral species since temperatures fluctuate more in an estuary than in the sea. Intertidal species are more tolerant for the same reason. A review of the literature reveals that eggs, larvae, and young fish are generally less tolerant of increased temperatures and would therefore suffer a greater loss because of this and their inability to avoid the heated effluents.

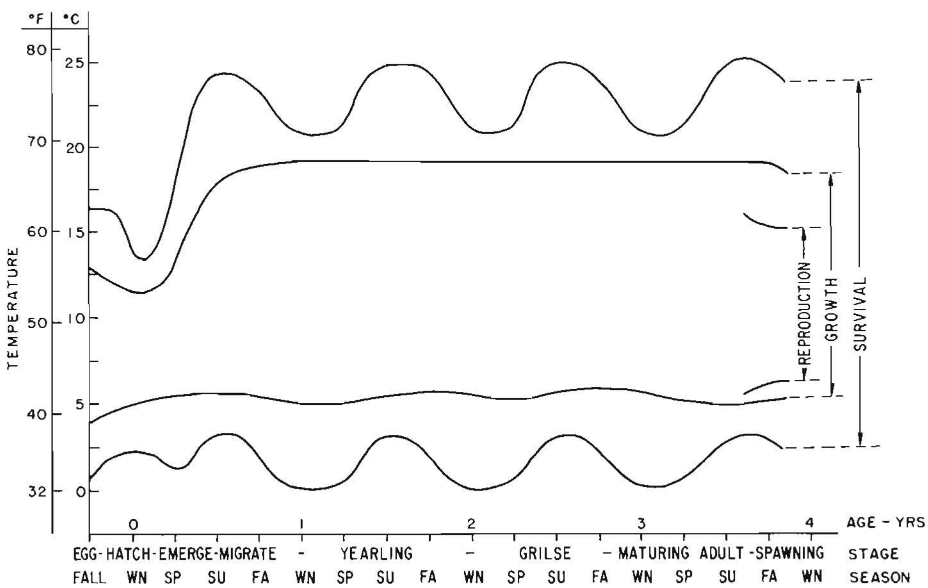

Figure 4.—Thermal requirements for various life processes of salmon. (From Brett, 1970.)

Sublethal Effects

The preceding paragraphs mention the most obvious of the effects that cooling systems and cooling waters have on marine organisms. These are the direct lethal effects where the end result is a dead fish decaying on the beach. The sublethal effects may be even more important, but they are usually much less obvious. These sublethal effects include increased susceptibility to predation and disease; effects on metabolism, growth, reproduction, behavior, the loss and damage of zooplankton; and synergistic effects.

Predation

Increased susceptibility to predation is one of the effects of sublethal exposure to increased temperatures, especially for juvenile fishes. Various researchers have found that a sublethal treatment to increased temperatures caused fry of sockeye salmon, *O. nerka;* yearling coho salmon, *O. kisutch;* juvenile chinook salmon, *O. tshawytscha;* and juvenile rainbow trout, *Salmo gairdneri,* to be all significantly more susceptible to predation than similar individuals not subjected to higher than normal temperatures (Sylvester, $972; Coutant, 1973). The thermal dose necessary to cause this susceptibility to predation was, in some cases, only a fraction of that necessary to cause loss of equilibrium in test fish.

Other sublethal effects of entrainment in the cooling and discharge systems of a thermal power plant may also increase the vulnerability of animals to predation. These include physical shock and abrasion, the effects of chemicals used as biocides, and the effects of temperature increases and pressure changes that cause gas embolisms. Gas embolism may either kill the fish directly or render it susceptible to predation. Power plants with once-through cooling could increase the rate of predation on Pacific Northwest species, especially on juvenile salmon that might be entrained or caught in the discharge plume.

Disease

The incidence of fish diseases (bacterial and parasitic) increases with elevated temperature. This relationship has been observed and studied in hatchery operations for many years. A review of the literature revealed that increased temperature was an important factor in most fish diseases (Ordal and Pacha, 1967). Studies with juvenile salmon and trout demonstrated that increased water temperatures intensified the effects of vibrio disease, kidney disease, furunculosis, and columnaris. Columnaris disease has been found to be exceptionally virulent during periods of high temperature. High temperatures in the Columbia River during the summer of 1941 and the consequent outbreak of columnaris disease decimated the sockeye salmon run that year. The literature is replete with incidents relating high temperatures to serious parasitic and bacterial diseases among aquatic organisms. Although cooling waters probably do not contribute significantly to fish diseases in the area at present, improperly located plants and discharges could cause problems in the future.

Reproduction

Spawning by marine animals may be stimulated by very slight differences in temperature. These changes may be as small as 1° or 2°C for some marine species. Truly oceanic species are usually more stenothermal (restricted to a narrow range of temperature) than estuarine species. A decrease in temperature usually delays spawning whereas an increase usually hastens spawning. Any alteration in spawning time could be harmful if the extremely critical balance of development, hatching, and availability of proper food for the young larvae is disturbed.

Some marine species, when exposed to higher than normal temperatures, do not spawn until returned to ambient temperatures; others may never spawn. Studies by the National Marine Fisheries Service revealed that temperature-treated female eulachon, *Thaleichthys pacificus,* of the Columbia River retained their eggs, whereas the control group spawned normally (Blahm and McConnell, 1971). Eggs of greenlings (*Hexagrammos decagrammos* and *H. stelleri*) subjected to treatments simulating conditions of tidal action and elevated temperatures from cooling waters did not hatch[1].

An increase of 18°F (10°C) could cause temperatures as high as 75°F (24°C) in condenser systems and in confined areas near outfalls in Puget Sound during the warmest months of the year. Very moderate temperature increases have been found to be lethal to Puget Sound Dungeness crab, *Cancer magister,* eggs (Strober and Salo, 1973). An 18°F increase in the cooling water from Puget Sound could cause these lethal temperatures in the condenser system in even the coldest months. Moreover, the eggs of marine species are buoyant and must remain near the surface for proper development. An increase in the water temperature could lower the density to a point where the eggs would sink and not develop.

The intake, condenser cooling, and heated water discharge systems of a thermal power plant could have an adverse effect on reproduction, depending on the proximity to important spawning areas and the life history pattern of the species. Gravid females and their eggs could be damaged by the intake system or by entrainment in discharge waters; spawning time could be altered. Eggs and larvae passed through a condenser cooling system would almost surely be damaged or killed.

Migration

Although few studies have specifically related temperature to the migration of adult anadromous fish, there is evidence that temperature is one of the important factors in the timing of migrations in the Columbia River (Coutant and Becker, 1968). There are records of abnormally high temperatures diverting or delaying migrations of Columbia River salmon (Fish and Hanavan, 1948; Major and Mighell, 1967), and experiments by the Bureau of Commercial Fisheries (now the National Marine Fisheries Service, NOAA) at Bonneville Dam indicated that adult salmon and steelhead preferred ambient or cooler water tem-

[1]Patten, B. G. 1974. High temperature tolerance of eggs and planktonic larvae of the kelp greenling, *Hexagrammos decogrammus,* and white spotted greenling, *H. stelleri.* Unpubl. manuscr. Natl. Mar. Fish. Serv., NOAA, Seattle, Wash., 11 p.

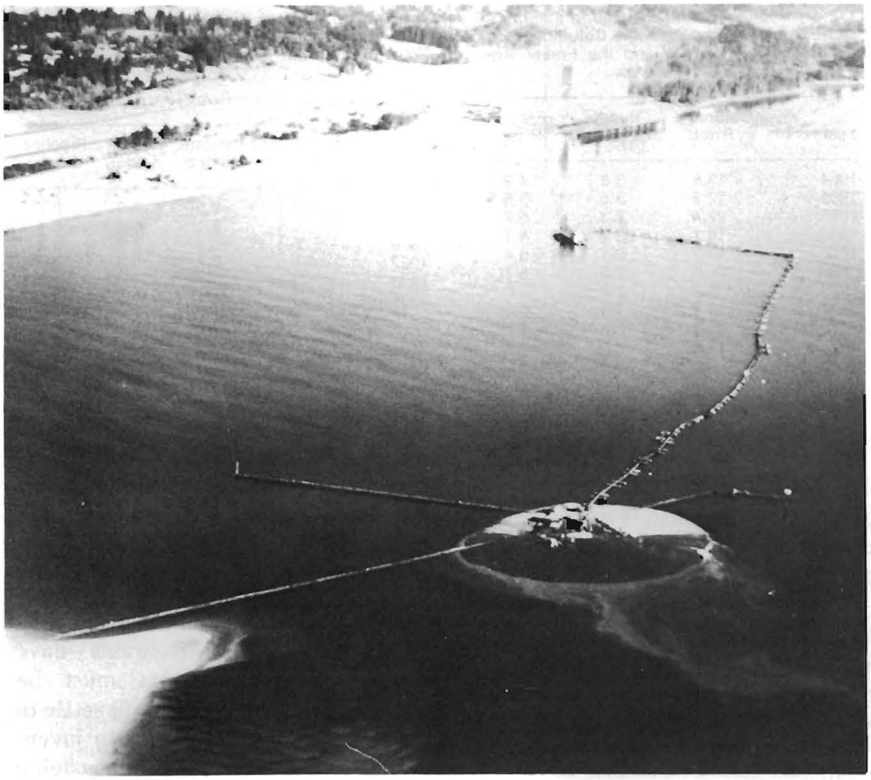

Figure 1.—Pipeline dredge in operation in the Columbia River at Hunters Bar near Kalama, Wash.

desirable. Hopper dredges in the Pacific Northwest vary in capacity from 500 to 3,000 cubic yards. They operate using suction intakes that can be lowered to a desirable depth with scrapers (or shoes) that feed a thin layer of bottom material through the suction pipe into the hopper (Fig. 2). When the hopper is filled, the vessel moves to a disposal site and flushes the material.

Other types of dredges found in the Pacific Northwest include bucket, side-caster, dipper, and ladder dredges. In addition, specially converted vessels are being used to move material through a "propellor-wash" operation (agitation dredging).

Navigation and development are the major reasons for dredging. Channel dredging is necessary to maintain commerce on our nation's waterways and is accomplished on a regular basis within the confines of a specific channel. Offshore dredging is normally conducted to obtain or recover mineral deposits. Normally the material is deposited inshore ("beaoh nourishment"). Estuarine and inshore dredging are accomplished primarily for channel maintenance, recovery of minerals, and for shellfish operations. The latter apparently has little application in the Pacific Northwest at this time but is of significant proportion in the eastern United States. Size of vessel and deeper draft vessels are increasing the need for the widening and deepening of our waterways. The distance to the entrance of a harbor from the ocean is becoming more important as costs per day of operation for the larger vessels increase. This necessitates the development of deeper ports closer to the ocean. Additional berthing spaces and turning basins are needed for commercial craft. The ensuing construction and development that follow any given port development increase the requirement for new dredging and disposal projects.

Further, the consideration of the exploration and mining of mineral resources from estuaries and offshore

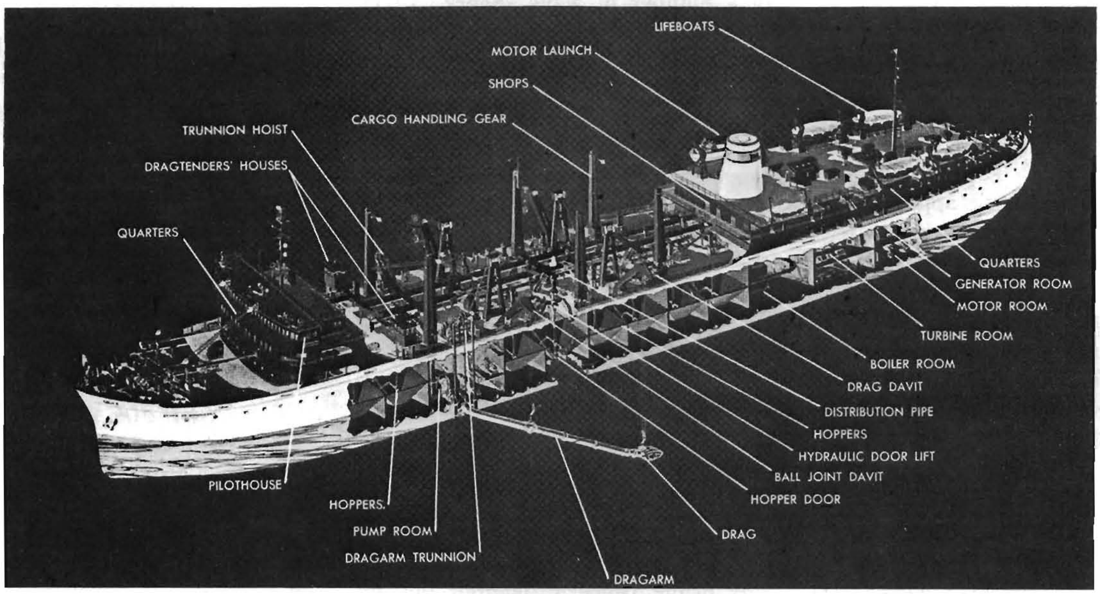

Figure 2.—Cross section of a typical hopper dredge.

areas will increase the demand for material displacement and for a knowledge of the resources that are impacted.

Quantities of Dredge and Disposal Material

Quantities of material that were dredged over a 10-year period from the Columbia and Fraser rivers and the Puget Sound area are shown in Table 1. Dredging on the Fraser River has increased; dredging in the Puget Sound area seems to have remained fairly stable, and the Columbia River dredging varies markedly from year to year. The quantities of material removed average 14.4 million cubic yards annually for the Columbia River and 5.6 million cubic yards annually for the Fraser River; on both rivers, the pipeline dredging method is used to remove most of this material (Table 2). The 14.4 million cubic yards of material dredged annually from the Columbia River would cover over 8,900 acres with 1 foot of material.

Table 1.—Quantities of material in millions of cubic yards dredged from the Columbia River, the Puget Sound area, and the Fraser River from 1964 to 1973.

Year	Columbia River	Puget Sound area	Fraser River
1964	13.6	3.8	4.9
1965	12.2	3.5	5.6
1966	22.4	2.3	5.2
1967	14.1	3.2	5.1
1968	13.7	3.1	5.4
1969	14.2	2.9	5.7
1970	8.7	3.8	5.0
1971	15.4	3.5	6.0
1972	13.3	2.8	6.3
1973	16.5	3.5	6.8
Total	144.1	32.4	56.0
Average	14.4	3.2	5.6

Table 2.—Type and quantity (millions of cubic yards) of dredge activity in the Columbia and Fraser rivers from 1964 to 1973.

Year	Columbia River		Fraser River	
	Hopper dredge	Pipeline dredge	Hopper dredge	Pipeline dredge
1964	5.1	8.5	1.2	3.7
1965	6.1	6.1	1.2	4.4
1966	6.1	16.3	0.9	4.3
1967	4.3	9.8	0.8	4.3
1968	3.6	10.1	1.0	4.4
1969	2.5	11.7	1.2	4.5
1970	4.3	4.4	1.1	3.9
1971	4.3	11.1	1.2	4.8
1972	6.3	7.0	1.2	5.1
1973	6.8	9.7	1.2	5.6
Total	49.4	94.7	11.0	45.0
Average	4.9	9.5	1.1	4.5

General Impacts of Material Removal

Dredging alters the topography of the channel. Between dredging operations, upstream water-borne material gradually restores the river bottom towards its natural shape. Continuous shoaling is the reason for the requirement of continuing programs of maintenance dredging.

In general there are three types of impacts on aquatic resources produced by material removal by dredges: 1) Mechanical effects; 2) turbidity; 3) other miscellaneous effects.

Mechanical Effects

Gutterhead dredging appears to be the type of operation with the most potential for creating adverse direct and indirect effects on the biological communities. This technique is usually utilized to remove loose or hard compacted materials in either new work or maintenance projects. Organisms can be dredged up and physically removed from the area, and the naturally vegetated material is destroyed. It has been shown that most species of aquatic organisms prefer a naturally vegetated bottom (Briggs and O'Connor, 1971). Hydraulic dredging uproots all vegetation, and more than a year may be required for recolonization of aquatic plants (Godcharles, 1971).

Clamshell dredging leaves depressions in the bottom substrate that affect the resource. These holes contain dissolved oxygen and hydrogen sulfide levels that will not sustain fish life or benthic invertebrates (Murawski, 1969).

The removal of benthic organisms by dredging prevents the benthic community from developing its full potential of productivity.

Turbidity and Sediment Effects

A review of the effects of suspended and deposited sediments indicated that sediment loads and deposited material will affect living resources and systems in a number of ways (Sherk, 1971). Turbidity and sediment load of the water column affect primary energy production, which occurs as a result of photosynthetic activities of planktonic algae. Secondary sources of energy conversion in shallow water are other algae, rooted plants, and benthic bacteria. The algae that convert the sun's energy are consumed by small animals adrift in water, or the algae sink and are eaten by bottom dwellers, and so forth through the food chain. However, the primary source of energy is the sun; turbidity can reduce or eliminate production in rivers, estuaries, and the ocean at a time when productivity could be at a maximum.

Miscellaneous Effects

A prime concern, pointed out by Thompson (1973), of the ecological effects of offshore dredging is the change in water clarity and the effects of bottom deposits on larval development and larval settlement. Larvae of bottom-dwelling invertebrates have subtle requirements that must be satisfied before the larvae will settle to the bottom and transform into juveniles. Evidence of the impact of dredging on larval forms of aquatic organisms indigenous to the Pacific Northwest is not available.

In the Pacific Northwest, large volumes of sediments which are high in levels of volatile solids and hydrogen sulfide have been found in major estuaries and bays. When these sediments are disturbed by dredging, the water column contains hydrogen sulfide concentrations that can be lethal to many organisms (Servizi, Gordon, and Martens, 1969). Although the lethal concentration is short-term, the result can be a substantial loss of a year class of indigenous or migratory organisms.

Although there has been concern expressed, little experimentation has been done to determine whether or not high concentrations of potentially deleterious chemicals in the mud are actually released into the water column during dredging in a manner that affects aquatic organisms.

IMPACT OF MATERIAL DISPOSAL ON LIVING RESOURCES

Background

The problem of how to dispose of dredged material is considered to be the number one problem throughout the nation for the U.S. Army Corps of

Engineers. Through the Corps' Waterways Experiment Station, a multi-million-dollar research project has been initiated by the Dredged Material Research Program to provide a better insight into the problem. It has been generally recognized that the impact of the disposal of dredged material far outweighs the problem of removing the material. In any case, thousands of acres of marshland have been lost and are continuing to be lost to various reclamation projects throughout this country. Additional volumes of dredged materials are being placed within freshwater swamps, shorelines, and backwater areas.

The problem compounds itself because deeper and wider channels are being dredged, resulting in the need to dispose of larger quantities of material; disposal sites, however, are becoming harder to locate. This problem is acute where the quality of bottom sediments is undesirable. The problems of material disposal are receiving considerable attention by researchers and in some projects receive high priority funding. In the Pacific Northwest, the Waterways Experiment Station, U.S. Army Corps of Engineers, is funding three research programs directed at finding solutions to the material disposal problems.

Thousands of acres of productive waterways have been lost through disposal of dredged material. Examples of loss of estuarine area due to dredge "spoiling" can be cited for most of our nation's major estuaries. Notable examples on the Pacific coast are in San Francisco Bay and the estuaries of the Columbia and Fraser rivers. The normal technique used in the river is to dredge the channel and place the "spoil" in dikes parallel to the river flow. Then, in subsequent maintenance-dredging operations, the dikes are raised above water level as the first step and filled from the dikes to the existing river bank for the second step. The amount of productive water area lost in the past has not been ascertained for areas of the Pacific Northwest, but the preservation of the aquatic resource requires that it be predicted for the future.

In-channel deposition of material has been resorted to in the rivers of the Pacific Northwest, but the effects on aquatic resources have not yet been assessed.

General Impacts of Material Disposal

General categories of direct effects of spoil disposal on aquatic organisms include:

1) Loss of organisms through incompatibility of dredge and disposal sites; 2) burial of organisms; 3) turbidity; 4) anoxia; 5) toxic chemical release. The impact of material disposal is first seen when the dredging barge or pipeline is moved to a specific dump site and the material is released. Special consideration needs to be given to the environment of the source of the material and the environment of the dump site. More profound impacts can be predicted to occur if the environments are not compatible, i.e., the removal of bottom organisms and material from fresh water or from slightly saline waters and the subsequent deposition in highly saline waters, or the movement of incompatible bottom material from one area to another, which can be disastrous to impacted organisms (Wilson, 1950).

Loss Through Burial

Burial of organisms has been noted as an important short-term impact on the resource; fixed epifauna, such as oysters, perish when covered by sediment (Lunz, 1942). Apparently, some benthic species (primarily invertebrates) reach the surface of newly deposited sediments after burial of more than 20 cm (Saila, Pratt, and Polgar, 1972). Larger and mobile invertebrates have survived burial under as much as 3 feet of material (Westley et al., 1973).

Turbidity and Water Quality

Mechanical or abrasive action of suspended silt and detritus is important to filter feeding organisms with respect to gill clogging, impairment or proper respiratory and excretory functioning, and feeding activity. Moreover, the deposition of suspended materials may interfere with or prevent reproduction by destruction of demersal eggs in upper estuarine nursery areas (Taylor and Saloman, 1968).

High turbidities can and do cause death from littoral suffocation and can disrupt primary productivity and community structure, increasing oxygen demand. There is a wide diversity between the types of materials that are being dredged and deposited and the potential effect on the aquatic resources. In general, the material continually dredged from an active navigation channel in the Pacific Northwest (the Columbia or Fraser rivers) differs markedly in quality from materials dredged from berthing spaces, old turning basins, or near outfalls from industries where pollution may have accumulated over a long period.

Silt loads above 4,000 ppm will prevent salmonids from migrating, while streams with silt averaging between 80 and 4,000 ppm are not desirable for supporting freshwater fisheries (Bell, 1973).

Miscellaneous Effects

Apparently, no far-reaching, long-lasting, or detrimental effects have been seen from the deposition of offshore sediments as beach fill; flora and fauna of beaches are accustomed to change and constant changes are part of the daily pattern of living (Thompson, 1973).

Changes in water quality as a result of large magnitudes of dredged material deposition have received a considerable amount of attention from biological researchers throughout the country (contained in review by Sherk, 1971). Effects on biological systems can be listed as follows: 1) Loss of habitat; 2) decreased euphotic zone depth; 3) increased oxygen demand; 4) increased nurient uptake and release; 5) reduced primary production; 6) community disruption.

The extent and importance of pesticide pollution in estuaries are not fully understood. Chlorinated hydrocarbons that are not of a magnitude to cause damage in specific organisms or constitute a human health problem do pose a threat, however, to other organisms through potential recycling or biological magnification. The potential effect of resuspended sediments containing pesticides and related contaminants is not clearly understood.

Evidence tends to support the contention that nutrient release and possible release of toxic materials occur in the water column with resuspension of bottom materials. This action could occur during dredging and subsequent material disposal from re-agitation during storms, floods, and beach erosion.

In addition, it has been found that organisms generally accumulate greater concentrations of chlorinated hydrocarbons when they are exposed to turbid waters (U.S. Fish and Wildlife Service, 1970); pesticide concentrations in fish tissues increase with turbidity.

Little information is available on the effect of heavy metals on organisms in the natural state, and levels in most water bodies and their significance are not well known. Trace quantities of heavy metals are known constituents of living matter, but in high concentrations these same metals are highly toxic. Toxicity of heavy metals varies with the presence of phosphorous and nitrogen compounds.

LITERATURE CITED

Bell, M. C. 1973. Fisheries handbook of engineering requirements and biological criteria. U.S. Army Corps Eng., Fish. Eng. Res. Program, Portland, Oreg., 497 p.

Boyd, M. B., R. T. Saucier, J. W. Keeley, R. L. Montgomery, R. D. Brown, D. B. Mathis, and C. J. Guice. 1972. Disposal of dredge spoil; problem identification and assessment and research and development. U.S. Army Corps Eng., Waterways Exp. Stn., Vicksburg, Miss., Tech. Rep. H-72-8, 121 p.

Briggs, P. T., and J. S. O'Connor. 1971. Comparison of shore-zone fishes over naturally vegetated and sand-filled bottoms in Great South Bay. N.Y. Fish Game J. 18:15-41.

Godcharles, M. F. 1971. A study of the effects of a commercial hydraulic dam dredge on benthic communities in estuarine areas. Fla. Dep. Nat. Resour., Div. Mar. Resour., Tech. Ser. 64, 51 p.

Lunz, G. R., Jr. 1942. Investigation of the effects of dredging on oyster leases in Duval County, Florida. *In* H. G. Hatch (compiler), Handbook Oyster Survey, Intercoastal Waterway, Cumberland Sound to St. Johns River. Spec. Rep., U.S. Army Corps Eng., Jacksonville, Fla.

May, E. B. 1972. Environmental effects of hydraulic dredging in estuaries. Ala. Dep. Conserv., Dauphin Island, Bull. 6, 85 p.

Montgomery, R. L., and F. H. Griffis, Jr. 1973. The Corps of Engineers dredged material research program. U.S. Army Corps Eng., Waterways Exp. Stn., Vicksburg, Miss., Misc. Pap. D-73-8, 36 p.

Murawski, W. S. 1969. A study of submerged dredge holes in New Jersey estuaries with respect to their fitness as a finfish habitat. N.J. Div. Fish Game, Misc. Rep. 2-M, p. 1-32.

O'Neal, G., and J. Sceva. 1971. The effects of dredging on water quality in the Northwest. U.S. Environ. Prot. Agency, Region 10, Seattle, Wash., 158 p.

Saila, S. B., S. D. Pratt, and T. T. Polgar. 1972. Dredge spoil disposal in Rhode Island Sound. Univ. R.I., Mar. Tech. Rep. 2, 48 p.

Servizi, J. A., R. W. Gordon, and D. W. Martens. 1969. Marine disposal of sediments from Bellingham Harbor as related to sockeye and pink salmon fisheries. Int. Pac. Salmon Fish. Comm., New Westminister, B.C., Can., Prog. Rep. 23, 38 p.

Sherk, J. A., Jr. 1971. The effects of suspended and deposited sediments on estuarine organisms. Univ. Md., Nat. Resour. Inst., Chesapeake Bio. Lab., Contrib. 143, 73 p.

Taylor, J. L., and C. H. Saloman. 1968. Some effects of hydraulic dredging and coastal development in Boca Ciega Bay, Florida. U.S. Fish Wildl. Serv., Fish. Bull. 67:213-241.

Thompson, J. R. 1973. Ecological effects of offshore dredging and beach nourishment: U.S. Army Corps Eng., Coastal Eng. Res. Cent., Wash., D.C., Misc. Pap. 1-73, 48 p.

U.S. Fish and Wildlife Service. 1970. Effects on fish resources of dredging and spoil disposal in San Francisco and San Pablo Bays, California. U.S. Dep. Inter., U.S. Fish Wildl. Serv., San Francisco, Calif., Spec. Rep., 36 p.

Westley, R. E., E. Finn, M. I. Carr, M. A. Tarr, A. J. Scholz, L. Goodwin, R. W. Sternberg, and E. E. Collias. 1973. Evaluation of effects of channel maintenance dredging and disposal on the marine environment in southern Puget Sound, Washington. Wash. Dep. Fish., Manage. Res. Div., Olympia, 308 p.

Wilson, W. B. 1950. The effects of sedimentation due to dredging operations on oysters in Copano Bay, Texas. Masters Thesis, Tex. A&M Coll., College Stn., 128 p.

MFR Paper 1221. From Marine Fisheries Review, *Vol. 38, No. 11, November 1976. Copies of this paper, in limited numbers, are available from D825, Technical Information Division, Environmental Science Information Center, NOAA, Washington, DC 20235. Copies of* Marine Fisheries Review *are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402 for $1.10 each.*